NSF nanoscale science and engineering at 20 years of NNI

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Nanotechnology Frontiers at 20 years of NNI
Proceedings, December 1, 2020, www.nseresearch.org/2020/

Outline

- **Long view of global nanotechnology development (2000-2040)**
  - *basics, system integration, divergence, diffusion*
- **International context**
  - *publications, patents, people, revenues*
- **NSF contributions**
  - *research, education, infrastructure outcomes*
- **Several challenges and trends**
  - *emerging topics, platforms, societal implications*

Nanotechnology R&D – last two decades

- **Importance of the unified and transforming definition in 2000**: *responsible* control & change at the nanoscale for society

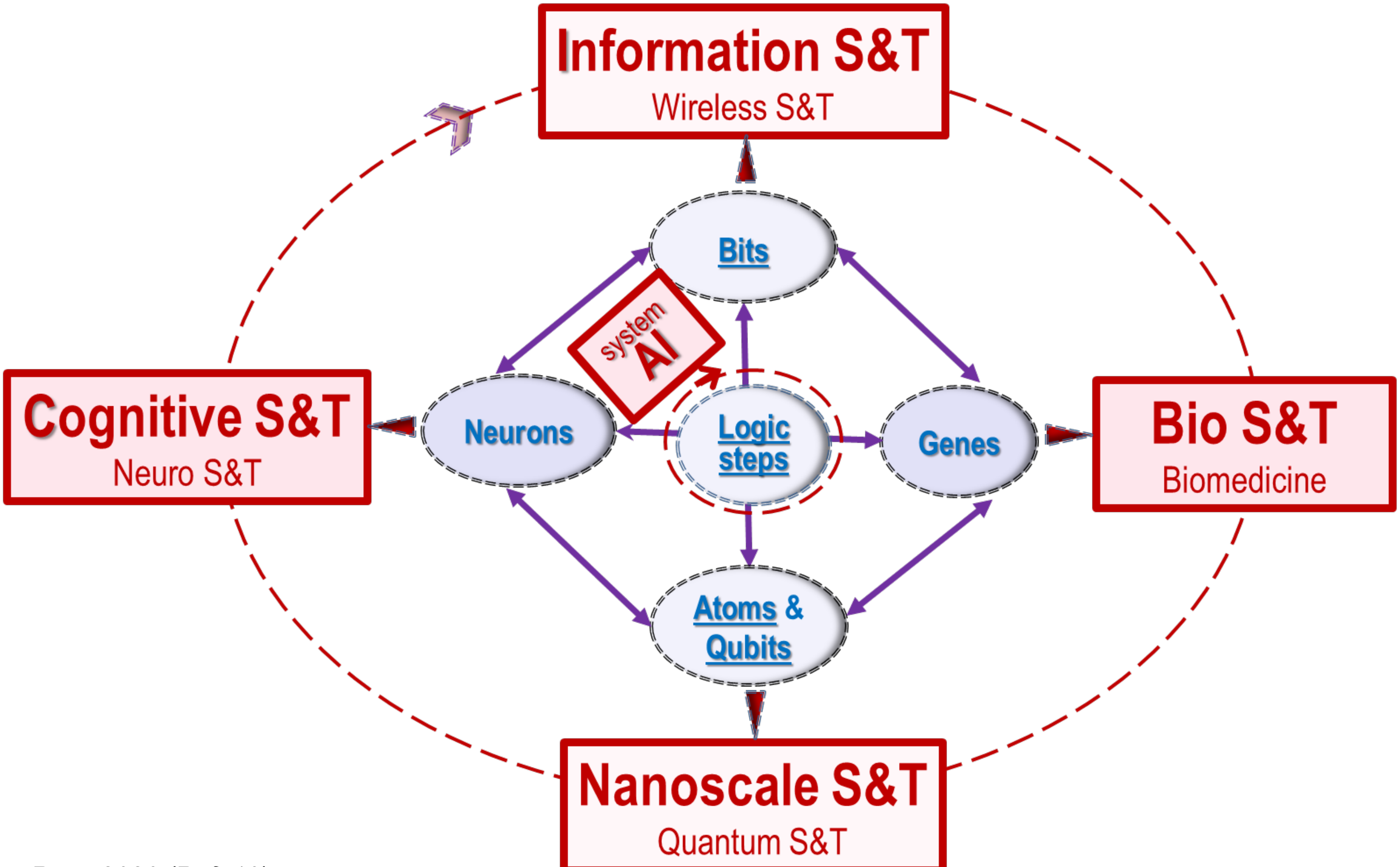
- **Nanotechnology is a foundational, general-purpose S&E field** - enabling NBICA. **It is a global science initiative.**

- **Nanotechnology today continues its growth, with ~20 spin-off areas** such as metamaterials, synbio and quantum IS

- After 2020, nanotechnology promises to become **a primary S&T platform for investments & venture funds**

Nano is a foundation of the *global S&T system,*

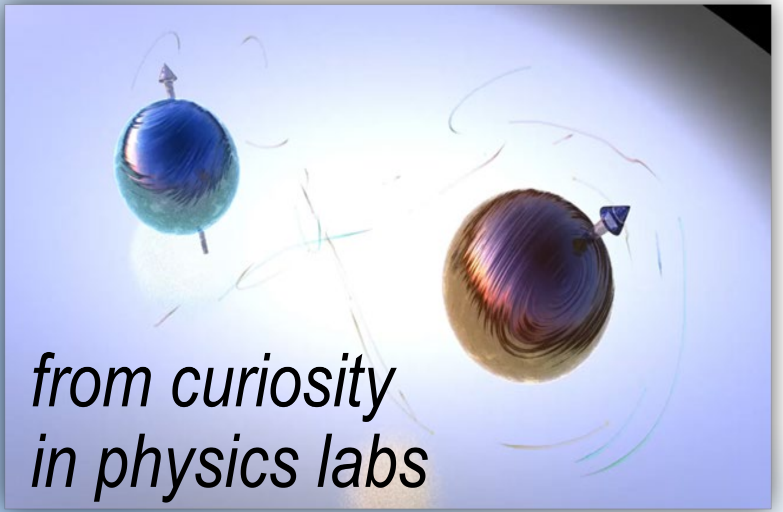
which is based on 5 elemental building blocks



Roco 2020 (Ref. 10)

Long view of establishing nanotechnology

2000 - 2040



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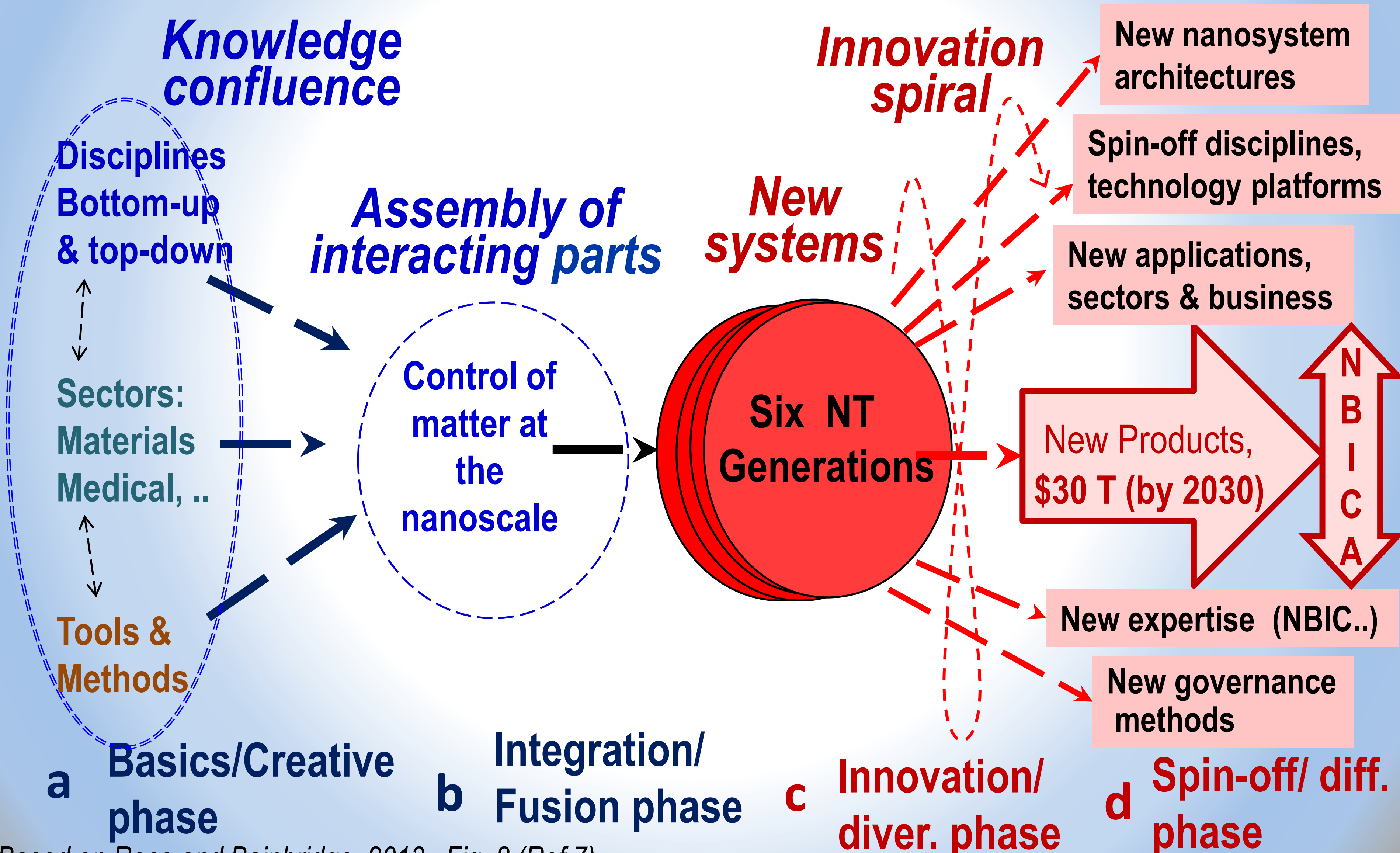
2000-2040 Convergence-Divergence cycle for establishing nanotechnology

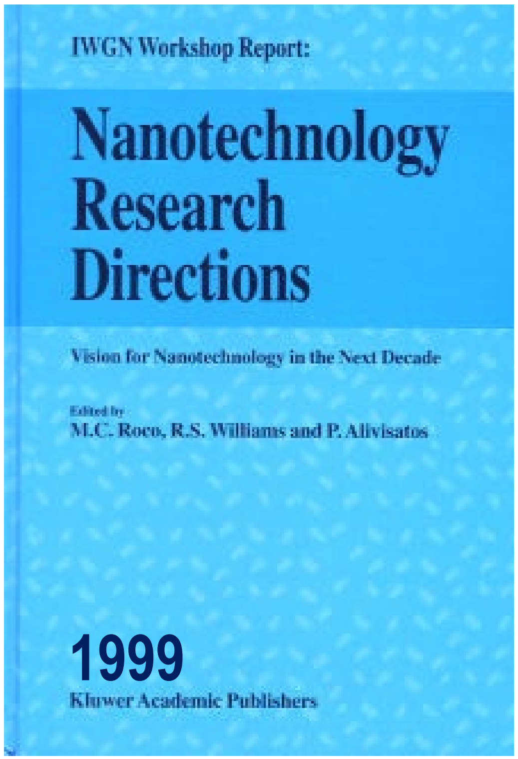


Based on Roco and Bainbridge, 2013 , Fig. 8 (Ref 7)

MC Roco, Dec 1 2020

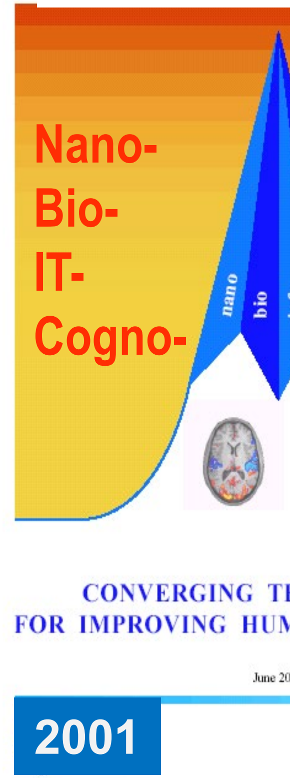
Nanotechnology: global vision reports

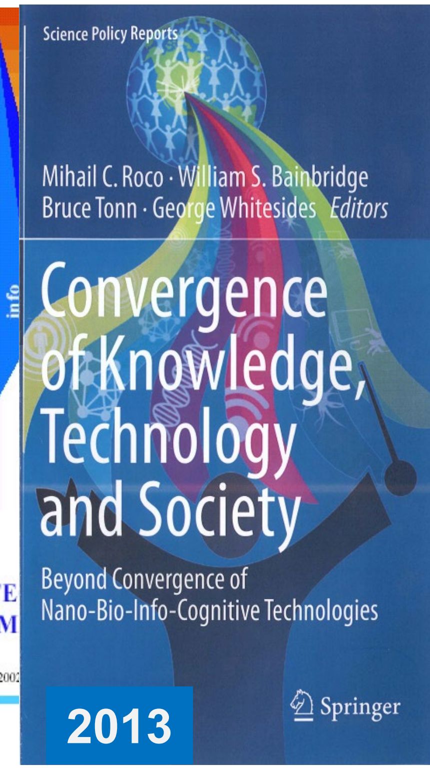
nano1 (2001-2010)



nano2 (2011-2020)

NBIC1&2 (2011-2040)

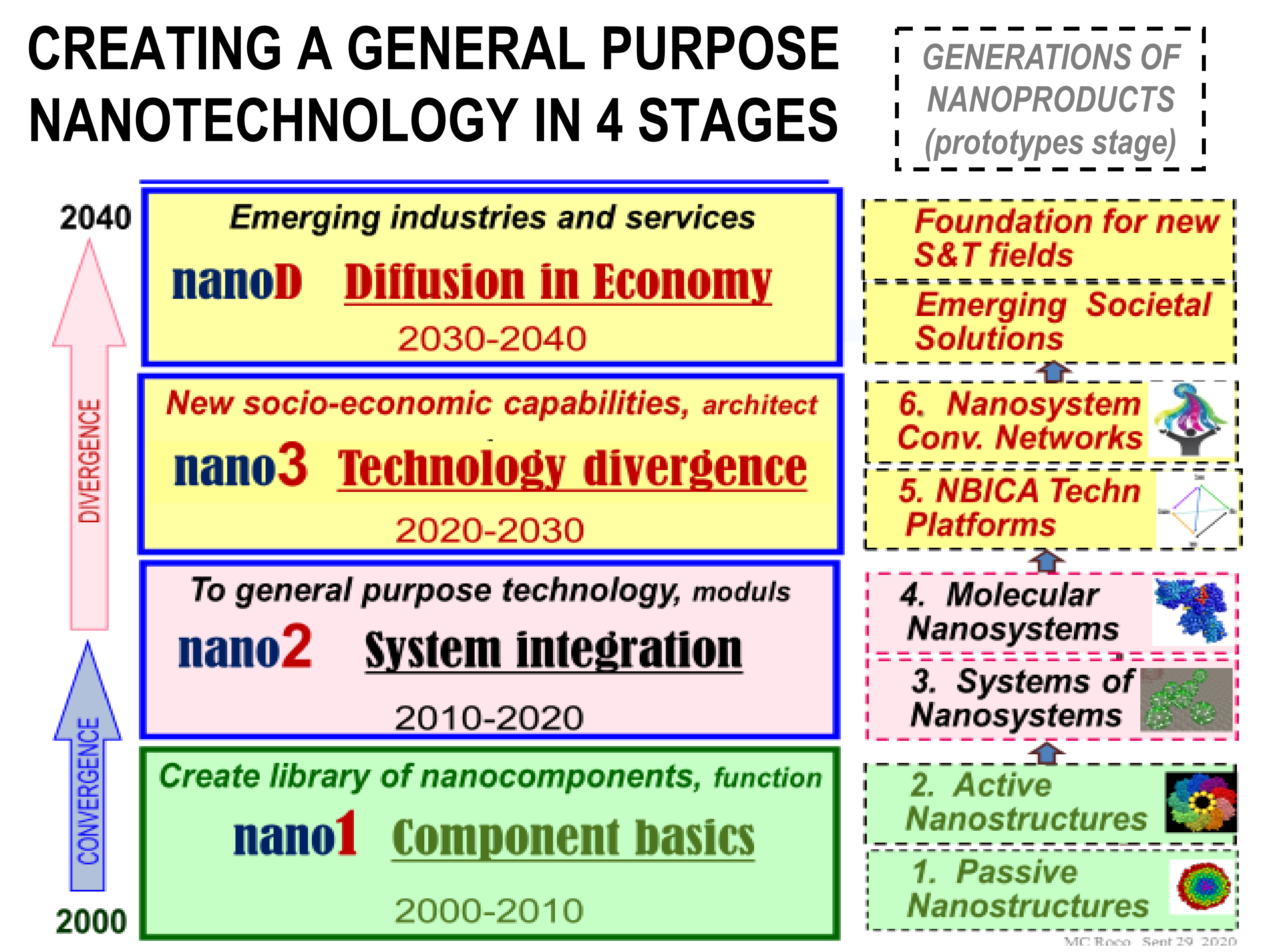




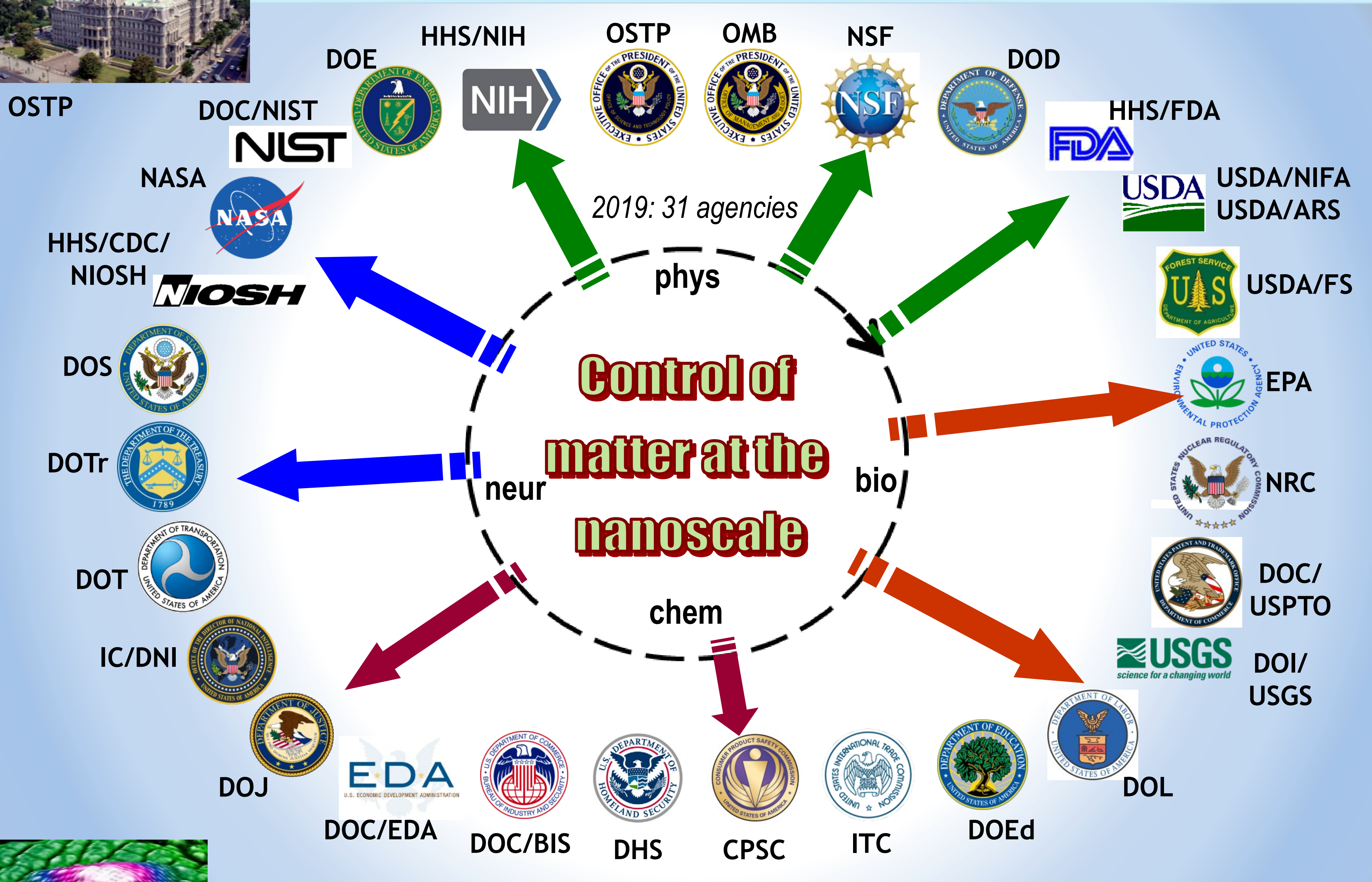
40 year vision: changing focus and priorities in 4 stages

- from basics, to system integration, divergence, diffusion

Input from >40 countries, Used in > ***80 countries****; Reports on scienceus.org/wtec/ (Refs 2-5)*


CREATING A GENERAL PURPOSE NANOTECHNOLOGY IN 4 STAGES
GENERATIONS OF NANOPRODUCTS (prototypes stage)
2040
2000
DIVERGENCE
CONVERGENCE
Emerging industries and services
nanoD Diffusion in Economy
2030-2040
New socio-economic capabilities, architect
nano3 Technology divergence
2020-2030
To general purpose technology, moduls
nano2 System integration
2010-2020
Create library of nanocomponents, function
nano1 Component basics
2000-2010
Foundation for new S&T fields
Emerging Societal Solutions
6. Nanosystem Conv. Networks
5. NBICA Techn Platforms
4. Molecular Nanosystems
3. Systems of Nanosystems
2. Active Nanostructures
1. Passive Nanostructures
MC Roco, Sept 29, 2020

Nanotechnology programs: S&T divergence



U.S. National Nanotechnology Initiative, 2000-2030

MC. Roco, Dec 1 2020

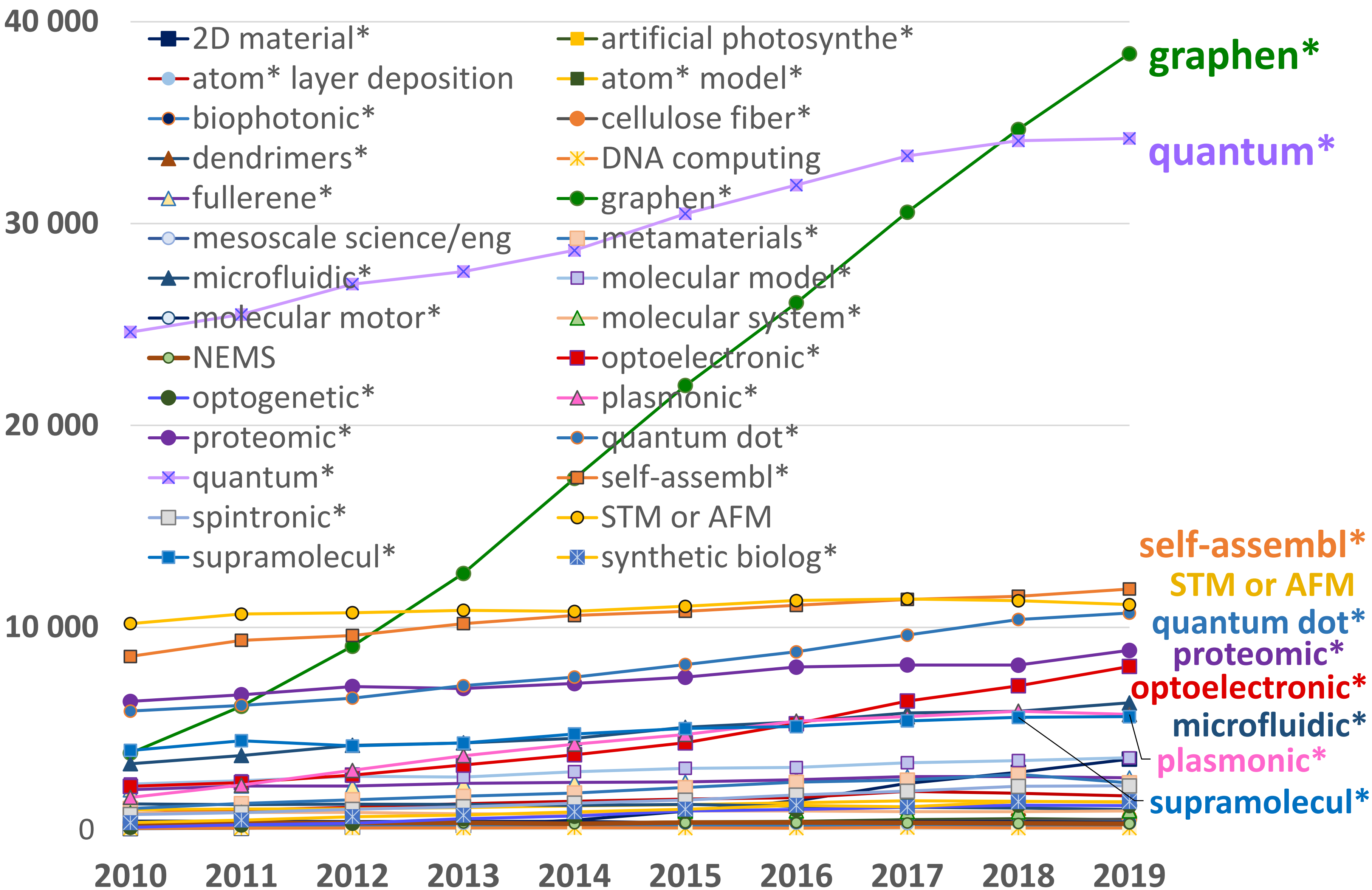
Nanotechnology spin-offs areas

- **Quantum systems** - *Quantum S&T* 2003; *NQI* 2018
- **Metamaterials** - 2004
- **Plasmonics** – 2004
- **Synthetic biology** - 2004
- **Modeling / simulation** - *Materials Genome Initiative* 2011
- **Nanophotonics** - *National Photonics Initiative* 2012
- **Nanofluidics**
- **Carbon electronics**
- **Nano sustainability**
- **Nano wood fibers**
- **. . . DNA nanotechnology, Protein nanotechnology, Nanosystems-mesoscale, Quantum BIO, Nano NEURO**

International context:

publications, patents, people, revenues

Nanotechnology topics in WoS from World: 2010-2019

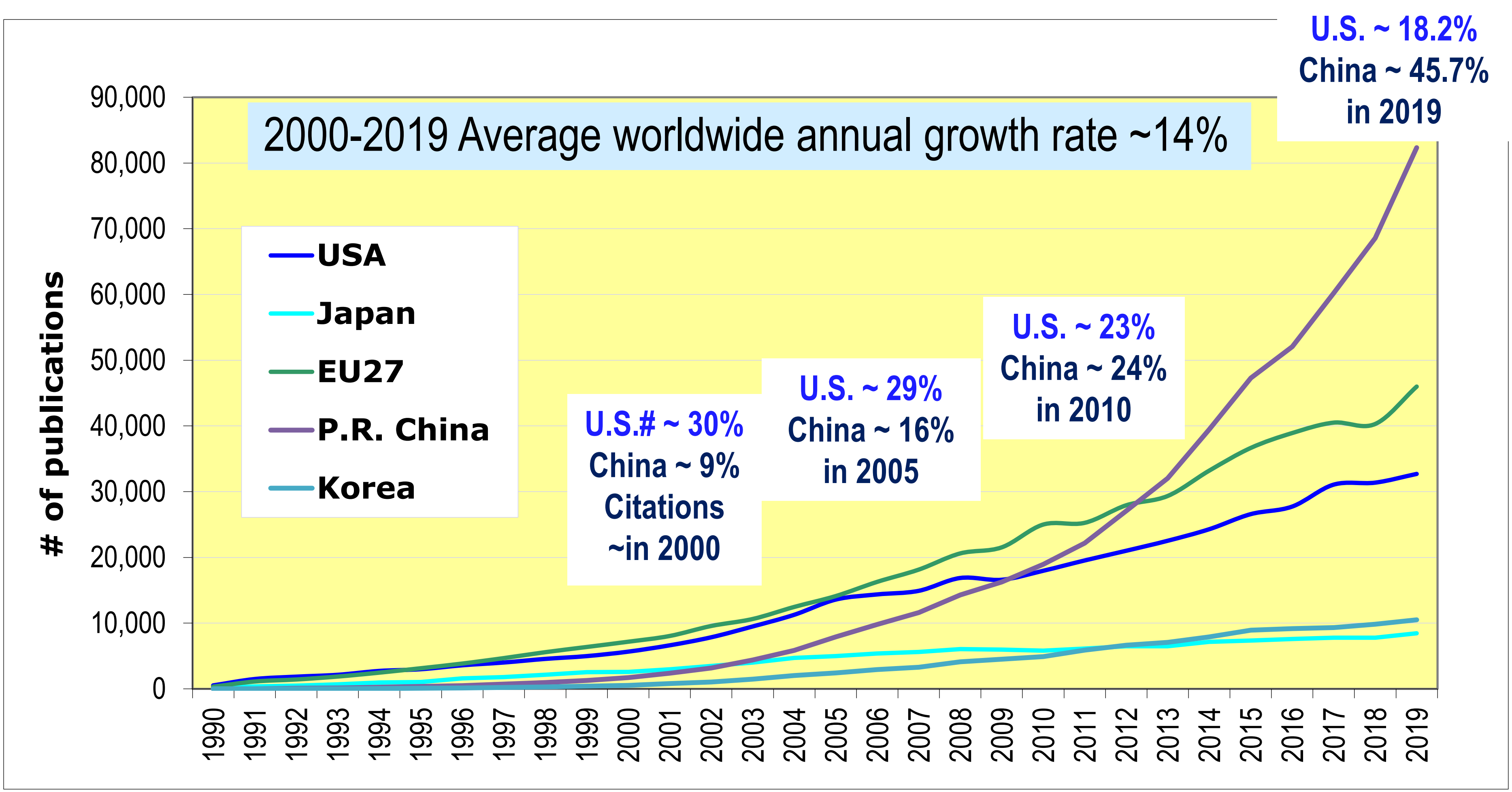


Keyword search (Roco and Nino de Guzman, 2020)

MC Roco, Dec 1 2020

Nanotechnology papers in the WoS: 1990 - 2019

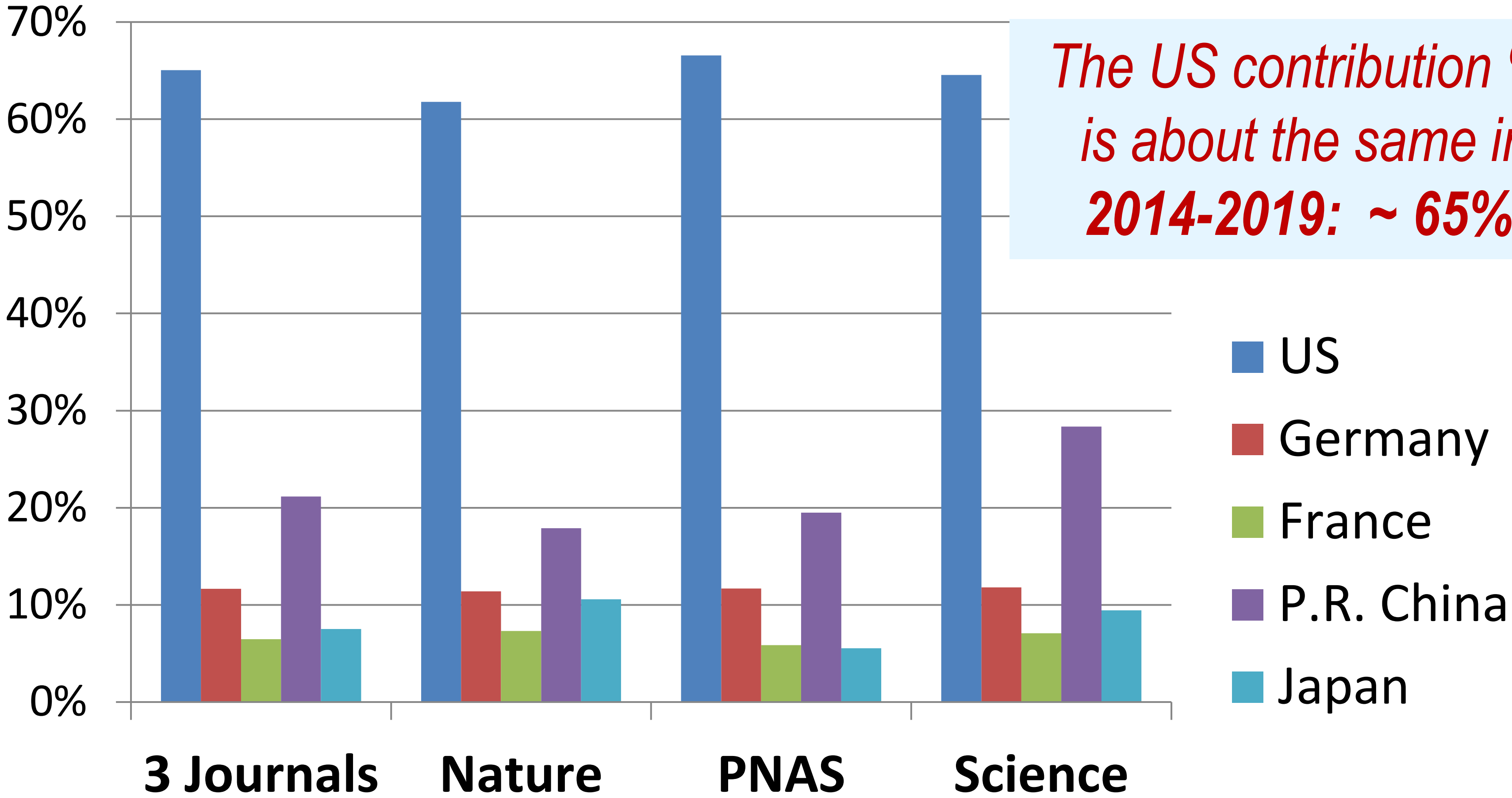
"Title-abstract" search for nanotechnology by keywords (update from NANO 2020, Fig 1; Ref 3)



Rapid, uneven growth per countries

Five countries' contributions to
Top 3 journals in 2019

"Title-abstract" search for nanotechnology by keywords (update from NANO 2020, Fig 1; Ref 3)

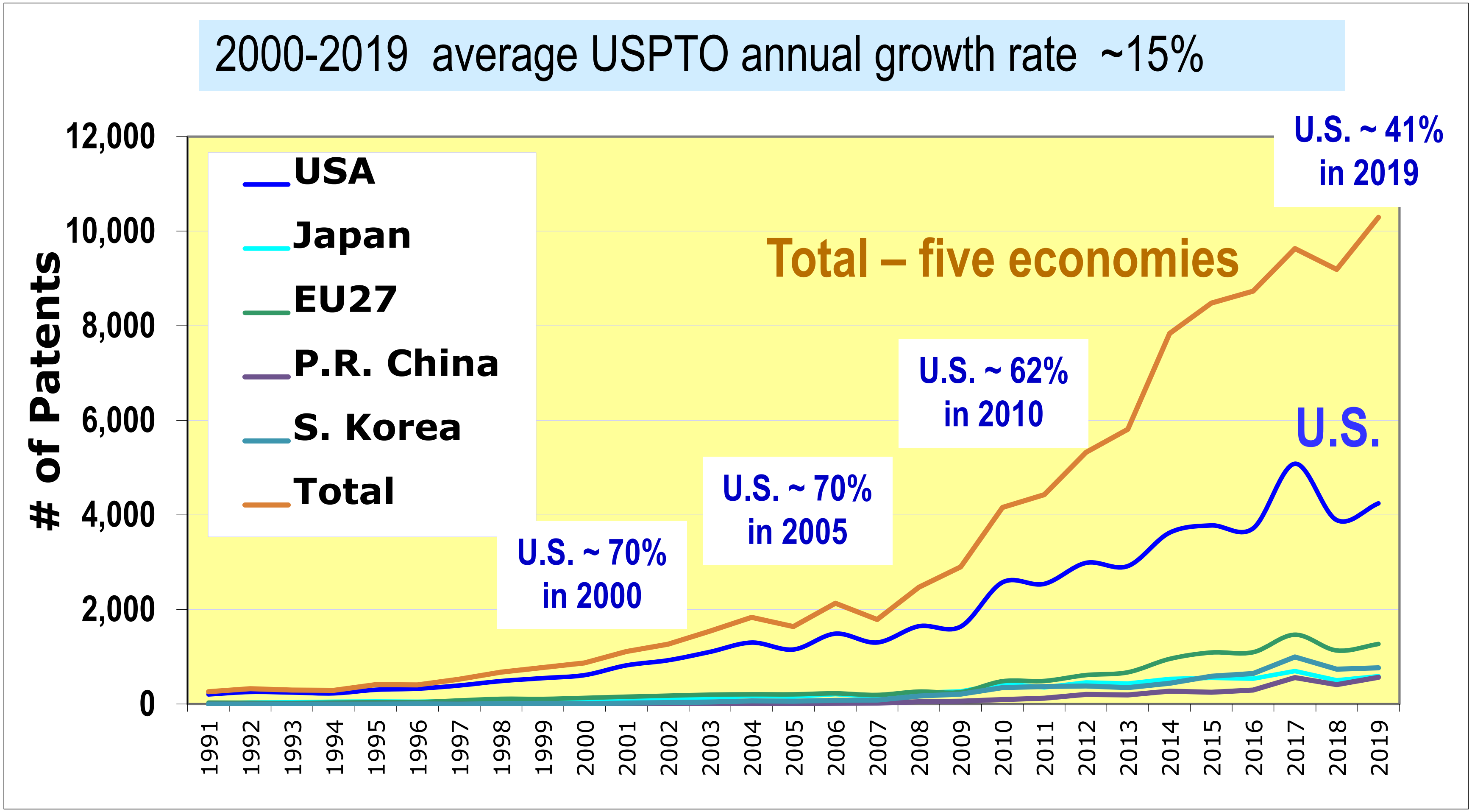


The US contribution % is about the same in ***2014-2019: ~ 65%***

* Each article is assigned to multiple countries if its authors have different nationalities. Therefore, the sum of percentages from five countries exceeds 100%

Nanotechnology patents at USPTO: 1991-2019

"Title-abstract-claims" search of nanotechnology by keywords , Zhu et al, Ref 7 (data May 2020)



U.S. patent authors maintain the lead at USPTO in 2019

MC Roco, Dec 1 2020

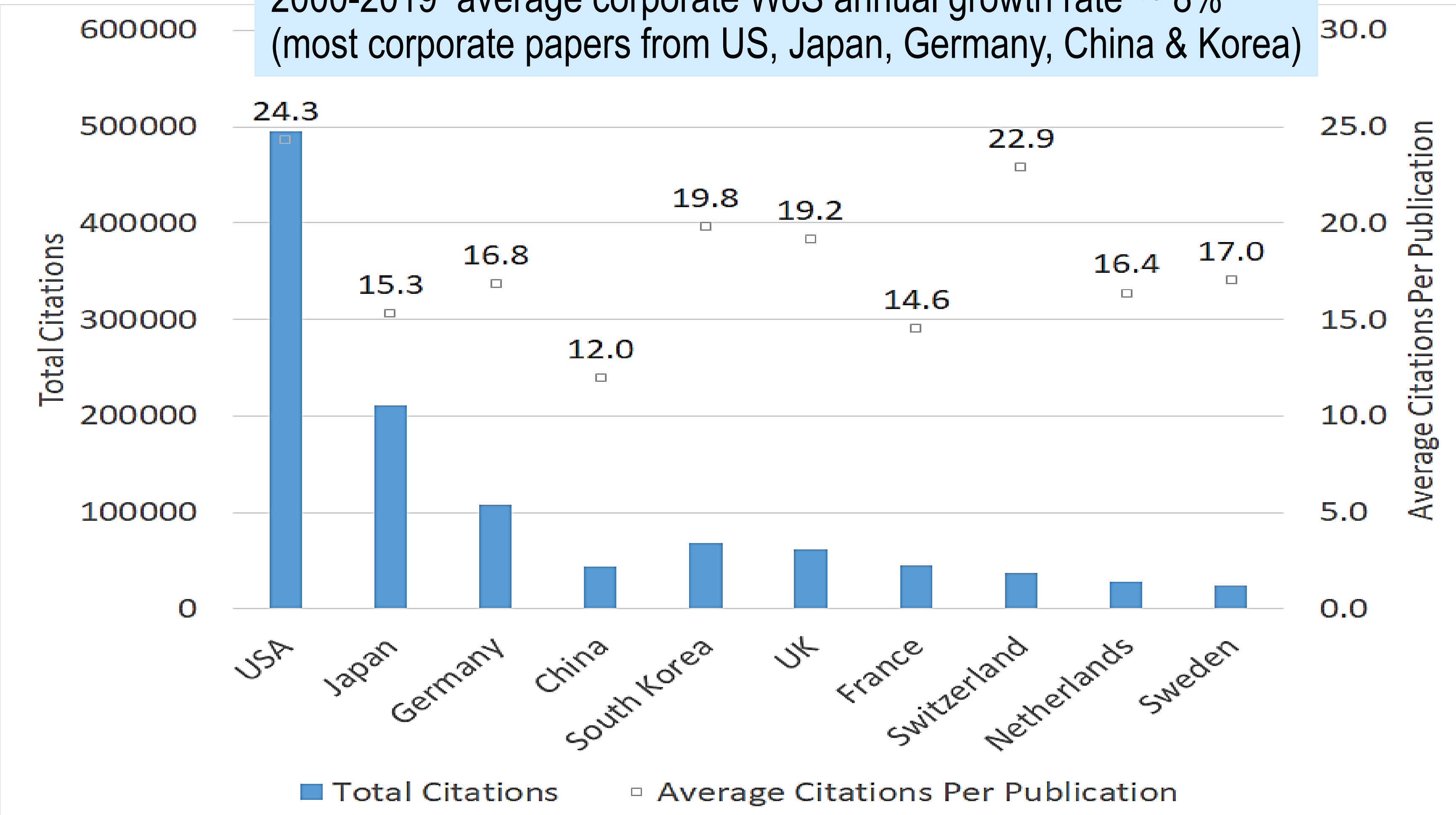
Summary estimates and growth rates of key nanotechnology indicators worldwide: 2000-2019

World	People -primary workforce	WoS papers	WIPO patent applic.	Revenues Est.	R&D Funding (gov + private)	Venture Capital
2000 *(survey)*	~ 60,000	18,953	2,158	~ $30 B	~ $1.2 B	~ $0.21 B
2010 *(survey)*	~ 660,000	78,987	23,510	~ $335 B	~ $18 B	~ $1.3 B
2000-2010 average growth	~ 27%	~ 15%	~ 27%	~ 27%	~ 31% (gov. 26%)	~ 30%
2019 *(lower-bound est.)*	~ 5 M	216,316 (~ 6% of all)	67,000	~ $2,500 B (up % of GDP)	multiple platforms	multiple platforms
2010-2019 average growth	~ 25%	~ 11%	~ 11%	~ 25%		
2000-2019 average growth	~ 26%	~ 14%	~ 20%	~ 26%		

Nano2020 Report, 2010 (Ref. 3), Lux Research (2013) and Roco 2018 (Ref 9) and WoS & Paper/Patent data May 2020 (Ref 10); Papers and Patents searched in title + abstract using 27 keywords MC Roco, Dec 1 2020

Number of corporate WoS publication citations by top ten countries: 2000-2019 *(Porter et al. 2020)*

2000-2019 average corporate WoS annual growth rate ~ 8%
(most corporate papers from US, Japan, Germany, China & Korea)



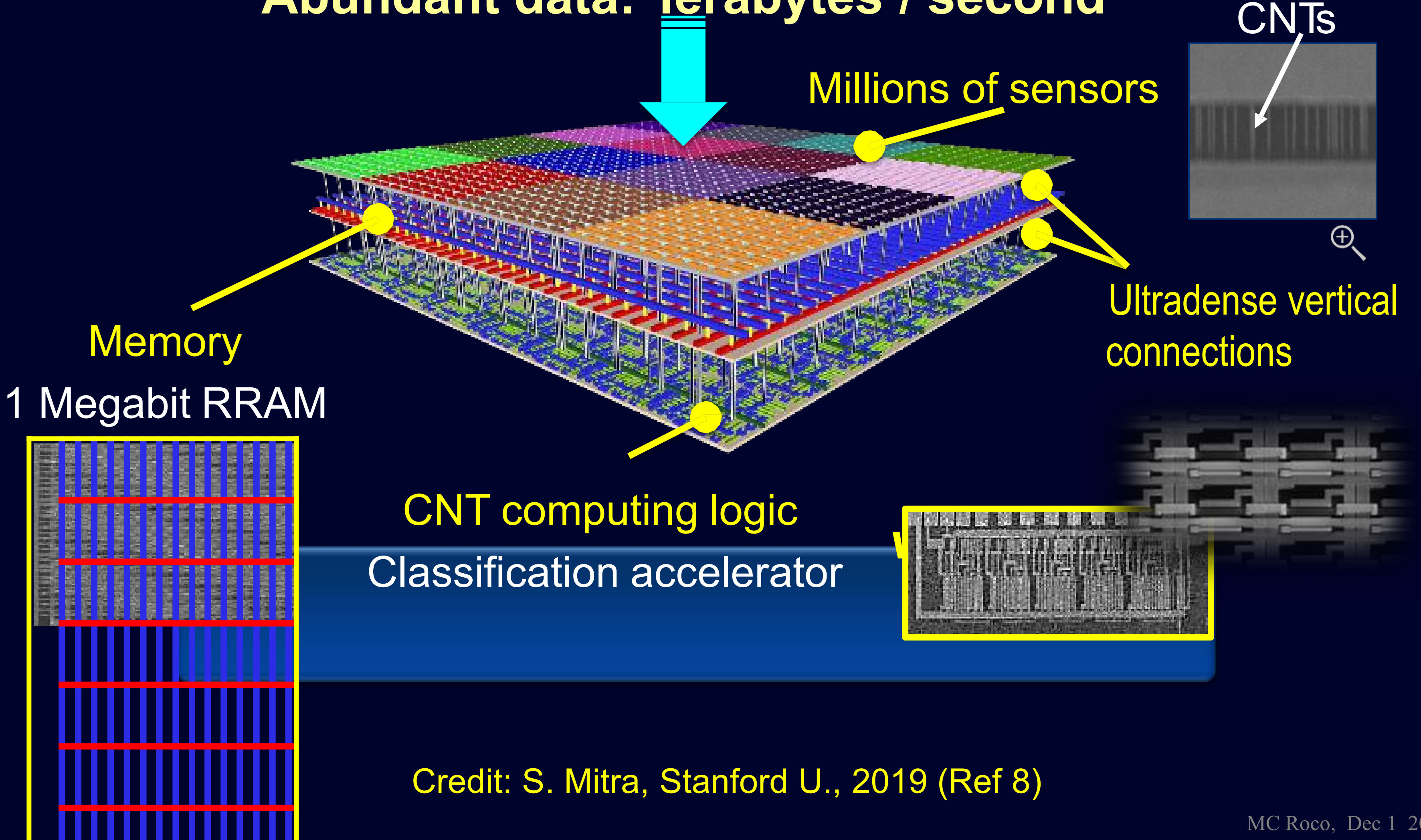
Source: A. Porter and N. Newman (Search Technology), R. Ward, J. Youtie, and P. Shapira (Georgia Institute of Technology), analysis of 53,200 global nanotechnology corporate publications (April, 2020) extracted from Clarivate Web of Science. Nanotechnology search terms based on Wang, Z., Porter, A. L., Kwon, S., Youtie, J., Shapira, P., Carley, S. F., & Liu, X. (2019). Updating a search strategy to track emerging nanotechnologies. Journal of Nanoparticle Research, 21(9), 199. Top 10 countries based on counts for the 1991-2019 period.

Illustrations of NSF contributions

Trend: 3D NanoSystems

Example

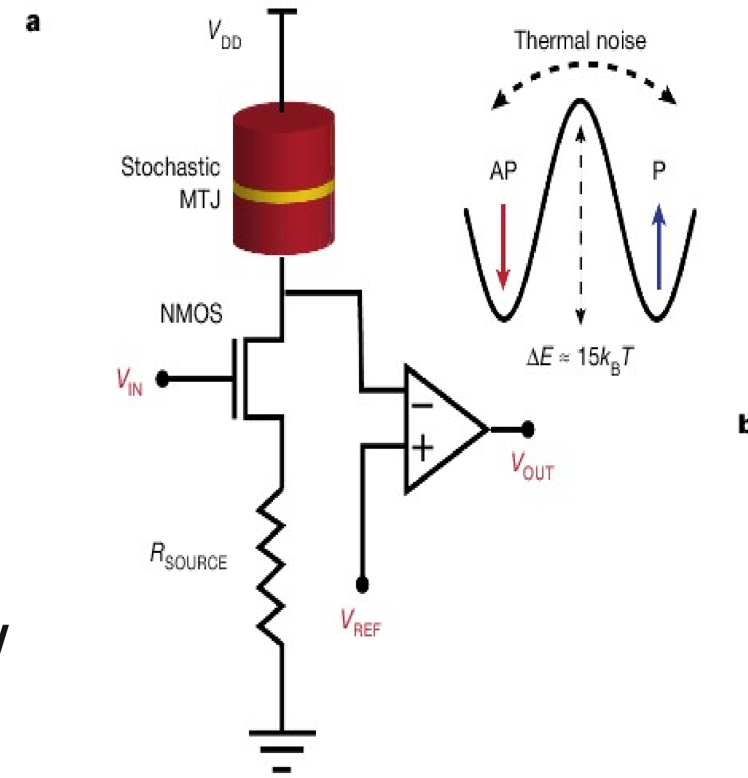
Abundant data: Terabytes / second



Credit: S. Mitra, Stanford U., 2019 (Ref 8)

Trend: Exploit probabilistic features: stochastic magnets, qubits, entanglement,..

Example: **8 "Probabilistic - bit" computer using stochastic nanoscale magnets** (Nature article. -*18 Sept 2019).*

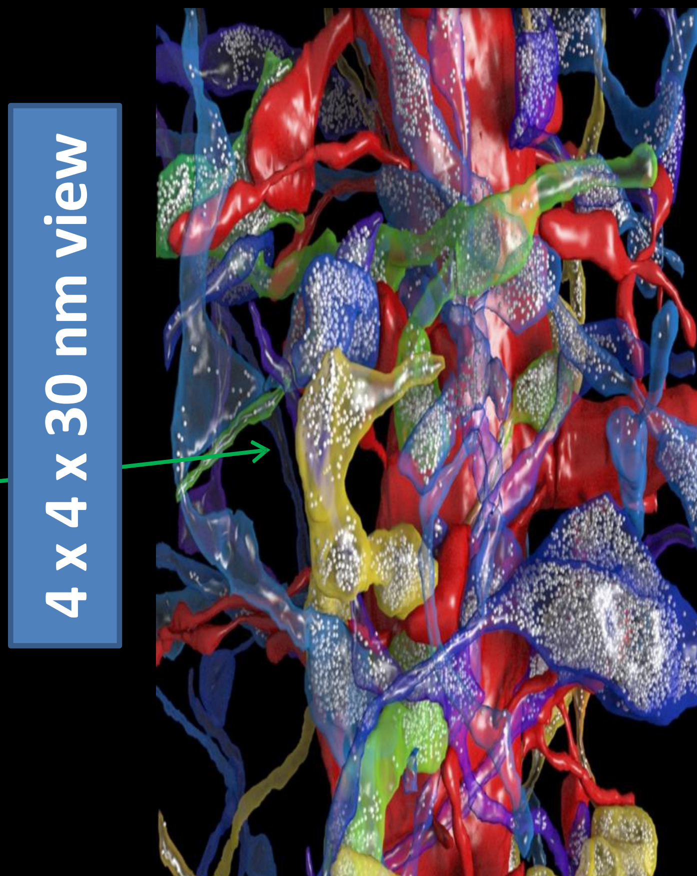


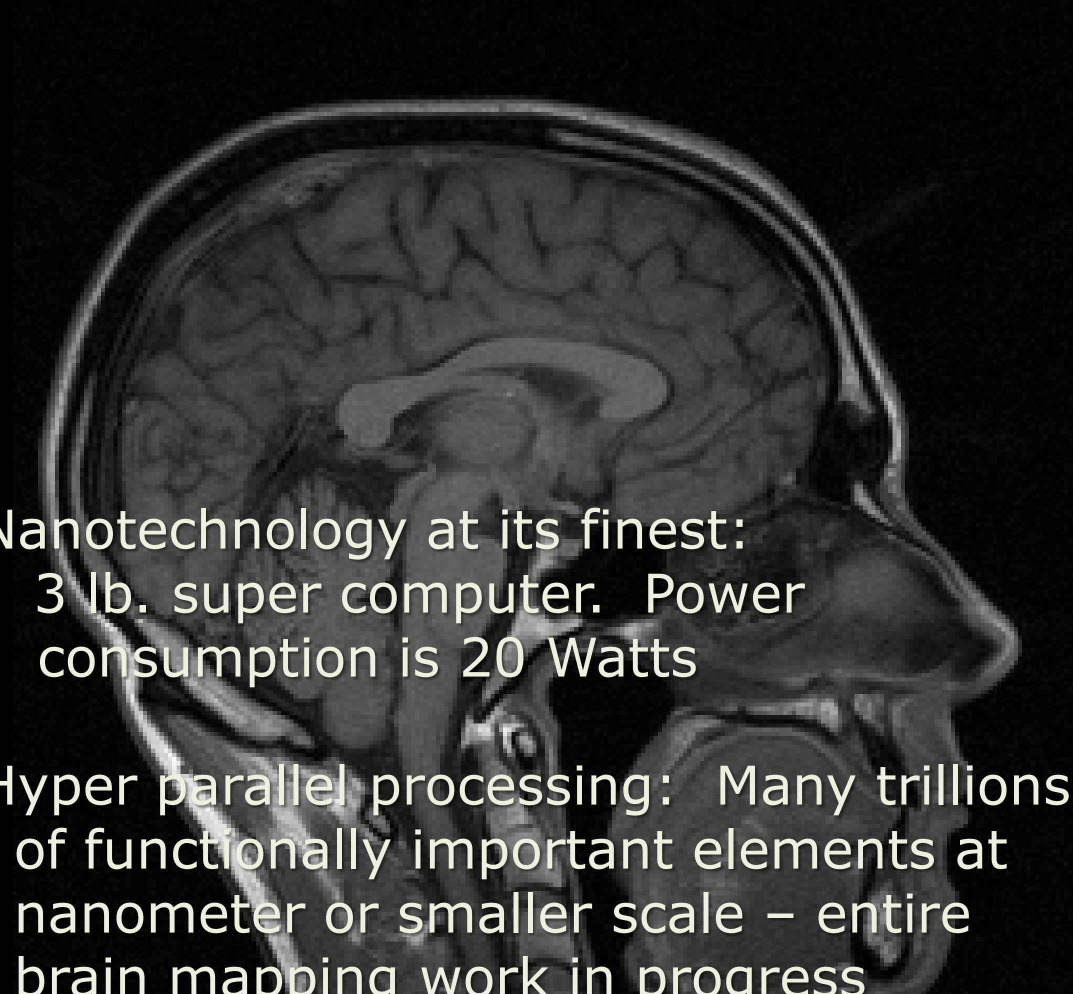
Addressing problems that only quantum computers were previously expected to solve efficiently.

Initial discovery by Supryio Datta's team (2017) (Ref. 8)

Trend: Nanoscale processes in brain

Example: Magnetic Resonance Image of human head





Nanotechnology at its finest:
3 lb. super computer. Power consumption is 20 Watts

Hyper parallel processing: Many trillions of functionally important elements at nanometer or smaller scale – entire brain mapping work in progress

Credit: J. Lichtman, Harvard U, 2019 (Ref 8)

Trend: **Nanobiotechnology**

Example: **Evolution of enzymes**

Frances Arnold, Nobel Laureate, 2018

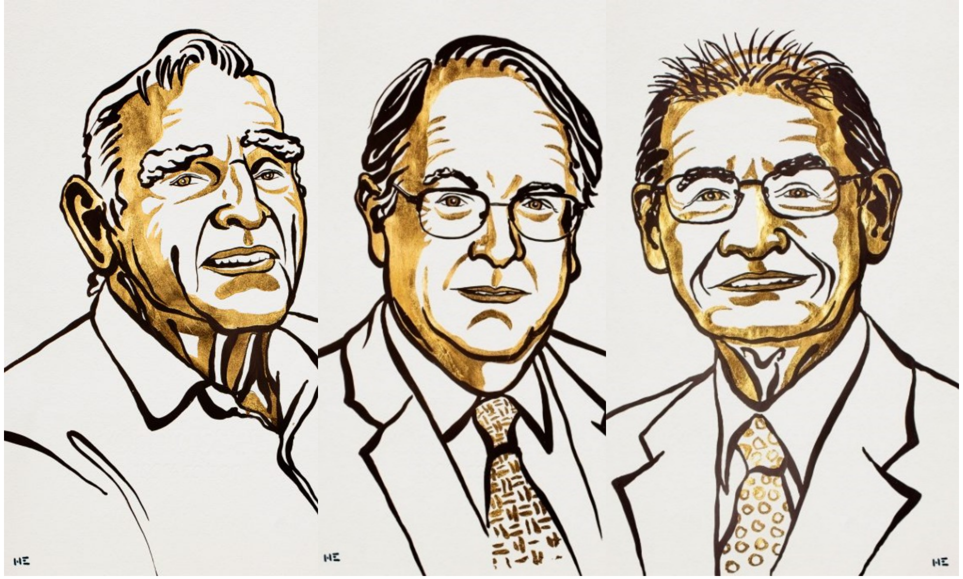
Using enzymes mutation and selection for fitness advantages via evolution one can produce novel synthetic catalysts for a sustainable chemistry/ chemical engineering

Credit: Directed Evolution: Bringing New Chemistry to Life
Frances H. Arnold, Angew Chem Int Ed Engl. 2018 Apr 9; 57(16): 4143–4148

Trend: **Nano for energy**

Example: **Development of lithium-ion batteries using nanostructured composite materials**

Nobel Prize in Chemistry 2019 awarded jointly to John B. Goodenough, M. Stanley Whittingham and Akira Yoshino



https://www.nobelprize.org/prizes/chemistry/2019/summary/

nano2

NSF Network for Computational Nanotechnology:

Hierarchical Nanomanufacturing Node (U. Illinois)

VISION

To simulate every step of the manufacturing process of a nano-enabled product

MISSION

To be the engine for design, simulation, planning, and optimization of nano-manufacturing processes

GOALS

- *Develop nanoMFG software tools*
- *Experimentally validate all tools*
- *Broadly disseminate*
- *Incorporate diversity at all levels*
- *Train next generation in development and utilization of nanoMFG software tools*
- *Create a sustainable framework*

Layered computational tools infrastructure

Nanoscale transport phenomena

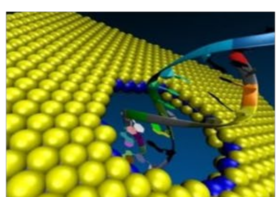
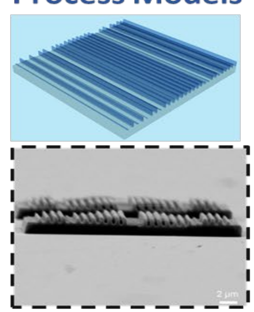


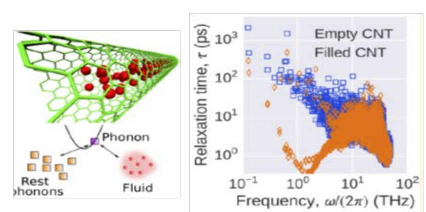
Illustration of a nanopore created in a 2D material by ion bombardment [N. Aluru]

Process Models



A flat optical lens created by TPL

Multiscale Transport Phenomena



Energy Dissipation in Fluid Coupled Nanoresonators [N. Aluru]

Nanoscale self-assembly

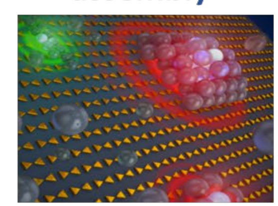


Illustration of plasmon-assisted particle assembly [K. Toussaint]

U. Illinois, Award: 1720701, http://nanomfgnode.illinois.edu/

Other topics with accelerated research in 2020

- US and global priorities, with international collaborations -

- **Foundation for the industries of the future**
  Example: Quantum, AI, Bio-econ, Wireless, Adv Manu

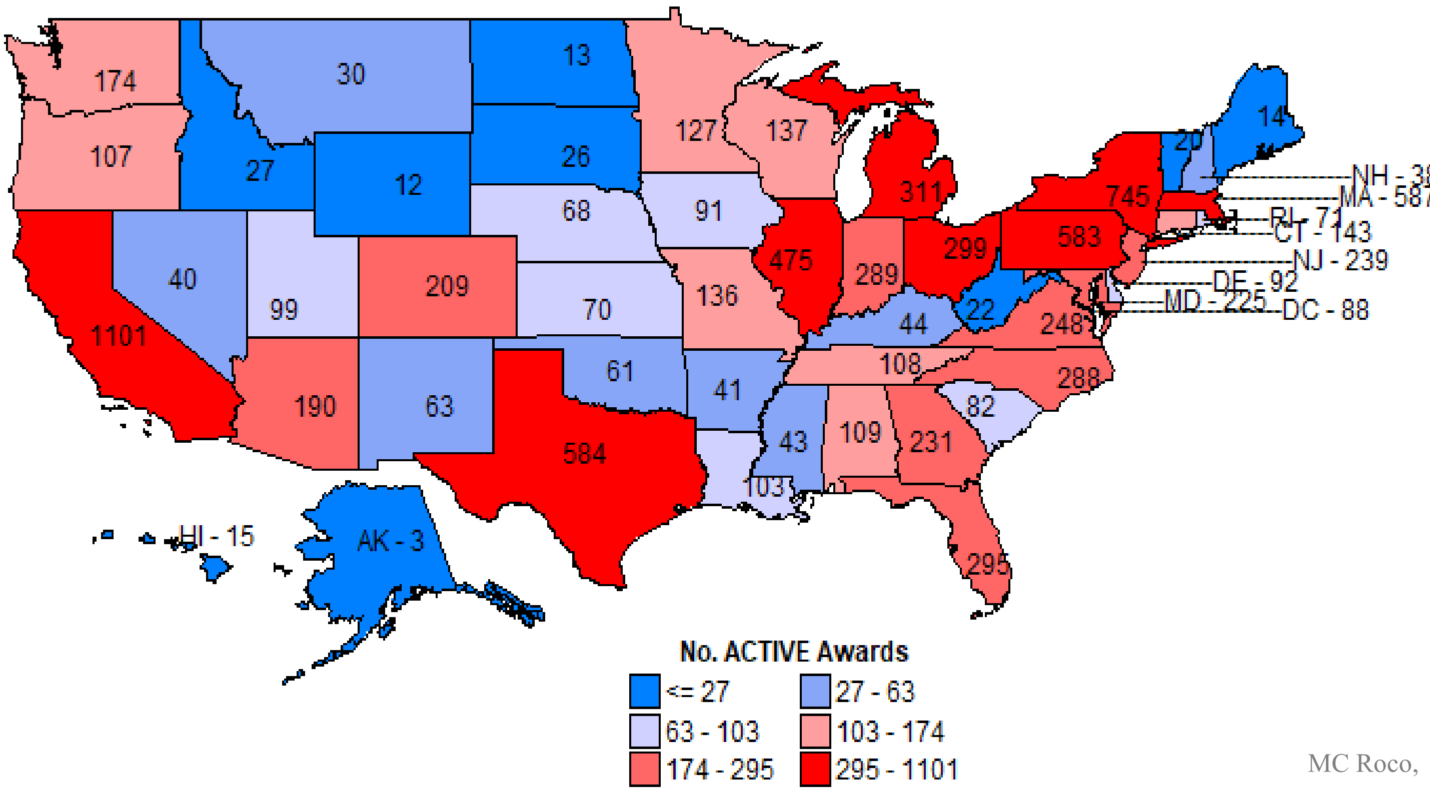
- **COVID19 Diagnostics, Treatment, Vaccines, dispersion** (several NSF's DCLs and core programs)
  Example: Nano-based vaccine manufacturing

- **Critical Aspects of Sustainability (CAS): Micro- and Nanoplastics** (MNP, DCL NSF 20-050):
  Example: transport phenomena and nano-EHS issues

- **Nanotechnology in agriculture:** nano-EHS issues

NSF's NS&E number active awards per state

FY 2020: Total Active Awards - over 8,000



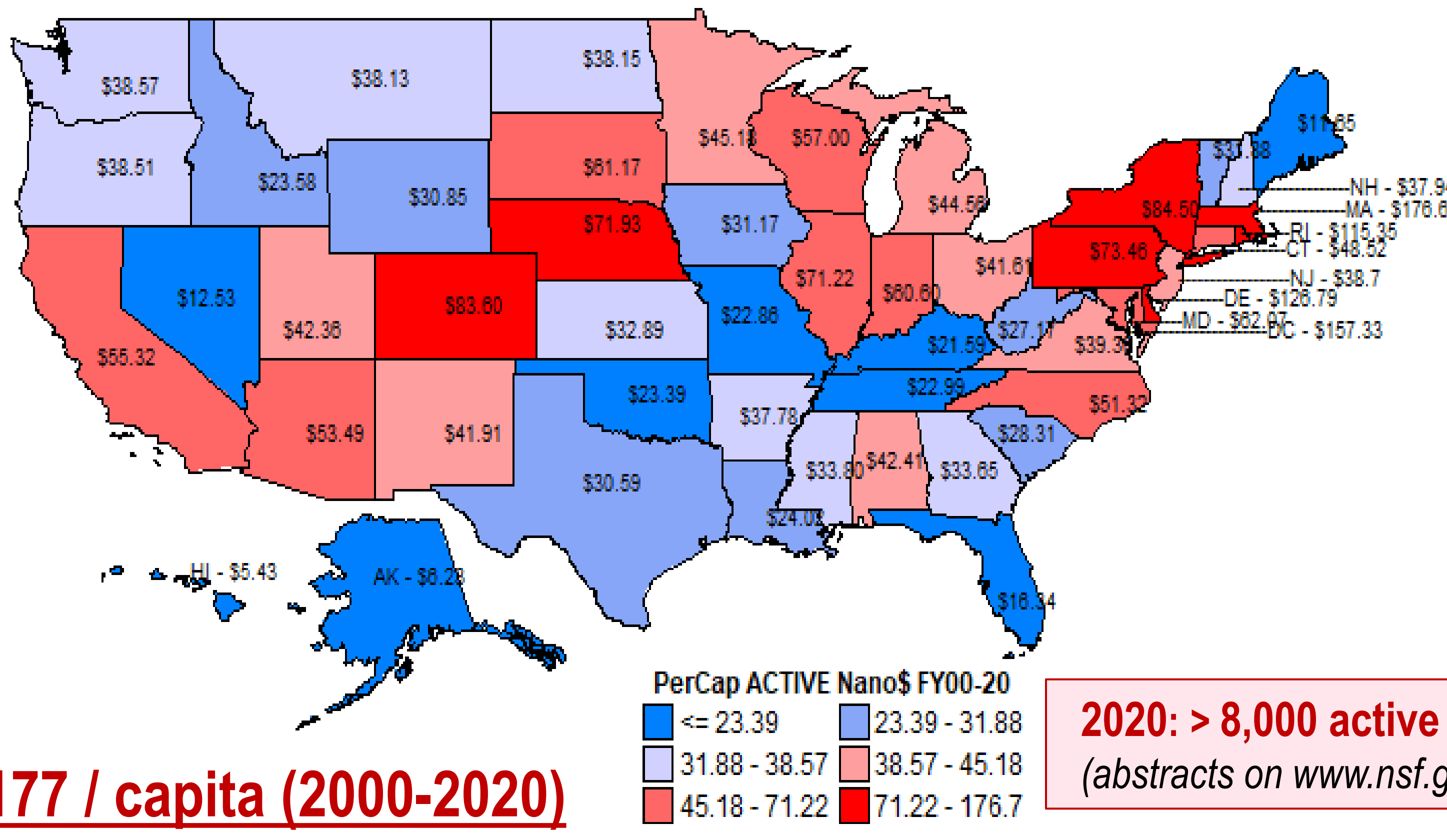
MC Roco, Dec 1 2020

#1 CA 1,101 awards in 2020

AK 3; AL 109; AR 41; AZ 190; **CA 1,101**; CO 209; CT 143; DC 88; DE 92; FL 295; GA 231; HI 15; IA 91; ID 27; IL 475; IN 289; KS 70; KY 44; LA 103; **MA 587**; MD 225; ME 14; MI 311; MN 127; MO 136; MS 43; MT 30; NC 288; ND 13; NE 68; NH 38; NJ 239; NM 63; NV 40; **NY 745**; OH 299; OK 61; OR 107; **PA 583**; PR 24; RI 71; SC 82; SD 26; TN 108; **TX 584**; UT 99; VA 248; VT 20; WA 174; WI 137; WV 22; WY 12

NSF's NS&E amount new awards per capita

FYs 2000 - 2020: U.S. average <u>~ $47.5 /capita</u>



<u>#1 MA $177 / capita (2000-2020)</u>

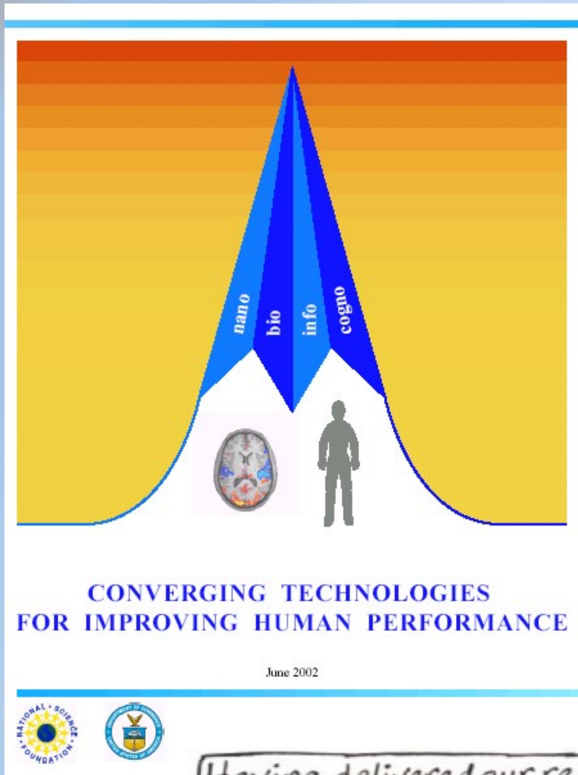
2020: > 8,000 active awards
(abstracts on www.nsf.gov/nano)

MC Roco, Dec 1 2020

AK 6.23; AL 42.41; AR 37.78; AZ 53.49; CA 55.32; **CO 83.60**; CT 48.52; **DC 157.33; DE 126.79**; FL 16.34; GA 33.65; HI 5.43; IA 31.17; ID 23.58; IL 71.22; IN 60.60; KS 32.89; KY 21.59; LA 24.02; **MA 176.67**; MD 62.07; ME 11.65; MI 44.56; MN 45.18; MO 22.86; MS 33.80; MT 38.13; NC 51.32; ND 38.15; NE 71.93; NH 37.94; NJ 38.70; NM 41.91; NV 12.53; NY 84.50; OH 41.61; OK 23.39; OR 38.51; PA 73.46; PR 23.81; **RI 115.35**; SC 28.31; SD 61.17; TN 22.99; TX 30.59; UT 42.36; VA 39.30; VT 31.88; WA 38.57; WI 57.00; WV 27.17; WY 30.85

Nature (2002): NBIC - ‘too exploratory’

“Futurists predict body swaps for planet hops”



2002: “Direct brain-to-brain communication and the transfer of minds between bodies seem more like the stuff of Hollywood movies than of government reports — but these are among the advances forecast in a recent report by the US National Science Foundation and Department of Commerce.”

“**Improving human performance has been a dream for centuries**,” says Mihail Roco, chairman of the government-funded National Nanotechnology Initiative, and lead author of the study ***Converging Technologies for Improving Human Performance***, released on 8 July — says that the **convergence …** may help to break those limits in the next 20 years.”

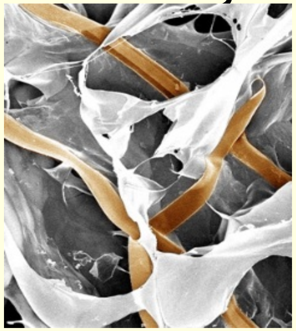
Challenges of nanotechnology development in 2020

NS&T continue to be driven by exploratory research. Topical examples are:

- **Ferroelectric materials, topological insulators**,…
- **Teleportation** of information and quantum calculations
- **Atomically precise manufacturing** (for quantum devices,….)
- **Nanodevices for AI**, and **AI design of nanosystems**
- **Synthetic biology, DNA editing and replacing**
- **Electronic & quantum biology and medicine**
- **Hierarchical self-assembly systems** that can adapt and evolve according to environmental changes ("room at the top")
- **Bottom-up agriculture** (molecular food supply)
- **Economical solutions** for medical care, distributed energy conversion and water filtration

Challenge: Creating new S&T platforms
- examples -

- **New system architectures**: guided self-assembling structures, evolutionary architectures, biomimetics--based, biorobotics-based, neuromorphic, adiabatic switching for IT, quantum systems… to be invented.
- **Nano-Bio-Info-Cognition-AI technology platforms, such as for hierarchical modular nanomanu. and personalized nanomed.**



- Genetic/single cell, neurotechnology, robotics - .... **to improve human potential**
- High productivity - high return **in all industry sectors**

Convergence science & technology in the time spiral:
three hierarchical S&T platforms (2000-2040)

III. CKTS: ***Convergence of Knowledge, Technology and Society***

(NBICA solutions + diffusion in economy)

II. NBICA: Nano-Bio-Info-Cogno-AI

(Converging foundational technologies)

I. - Nano: Nanotechnology

- IT: Information, networking, digitization

- AI: Artificial intelligence systems

(General-purpose S&T fields / tools)

nano3
2020-2030

Challenge: Create nano-inspired solutions and tools for the industries of the future

- **Artificial intelligence (AI)** – use and design nanosystems
- **Quantum Information S&T** - a part of nanoscale S&T
- **Advanced Wireless (5G, IoT)** - including use nanosystems
- **Advanced Manufacturing** - a focus on nanomanufacturing
- **The Bioeconomy** - a focus on nanobiotechnology

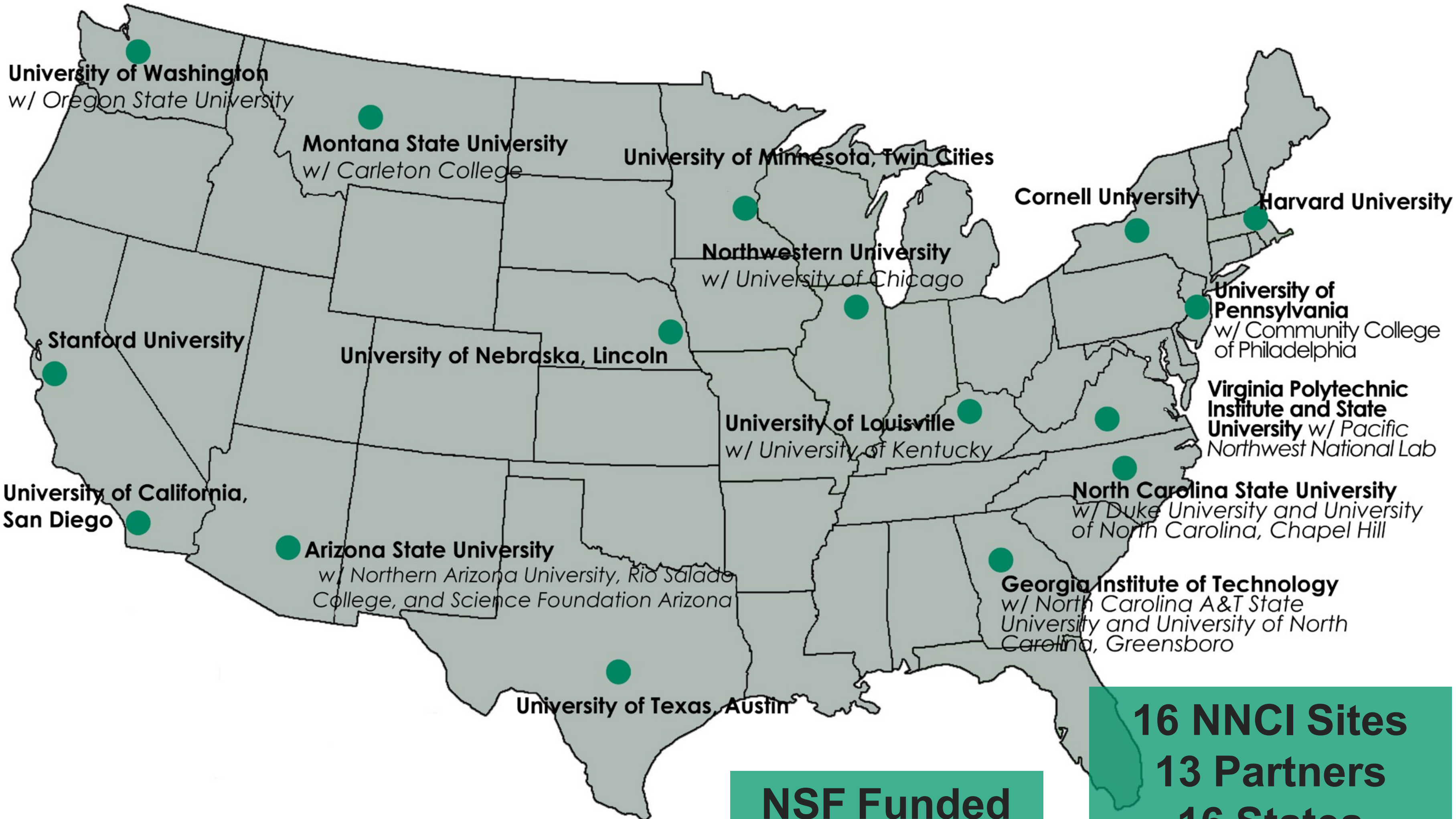
- **Sustainable society** – for materials, water, energy, env
- **Independent aging** – includes nano-medicine & robotics
- **Increase human capacity** – physical, mental, group

nano3
2020-2030

Challenge: Nano-inspired solutions require skilled people and physical infrastructure

- **Integrated centers for more efficient, responsible transition from fundaments to technology platforms & applications**
  Ex: US/NNCI, France/Minatec, Japan/Net, NL/IMEC, China
- **High performance facilities**
  Ex: **High Magnetic Field Beamline at Cornell Univ.** (2020) mid-scale infrastructure investment
- **Human resources, new organizations**
  Ex: **Micro-Nano Technology Education Center,** Pasadena City College, July 1, 2020-; for Community Colleges together

National Nanotechnology Common Infrastructure Network 2020



NSF Funded
2015 - 2025
$165M total

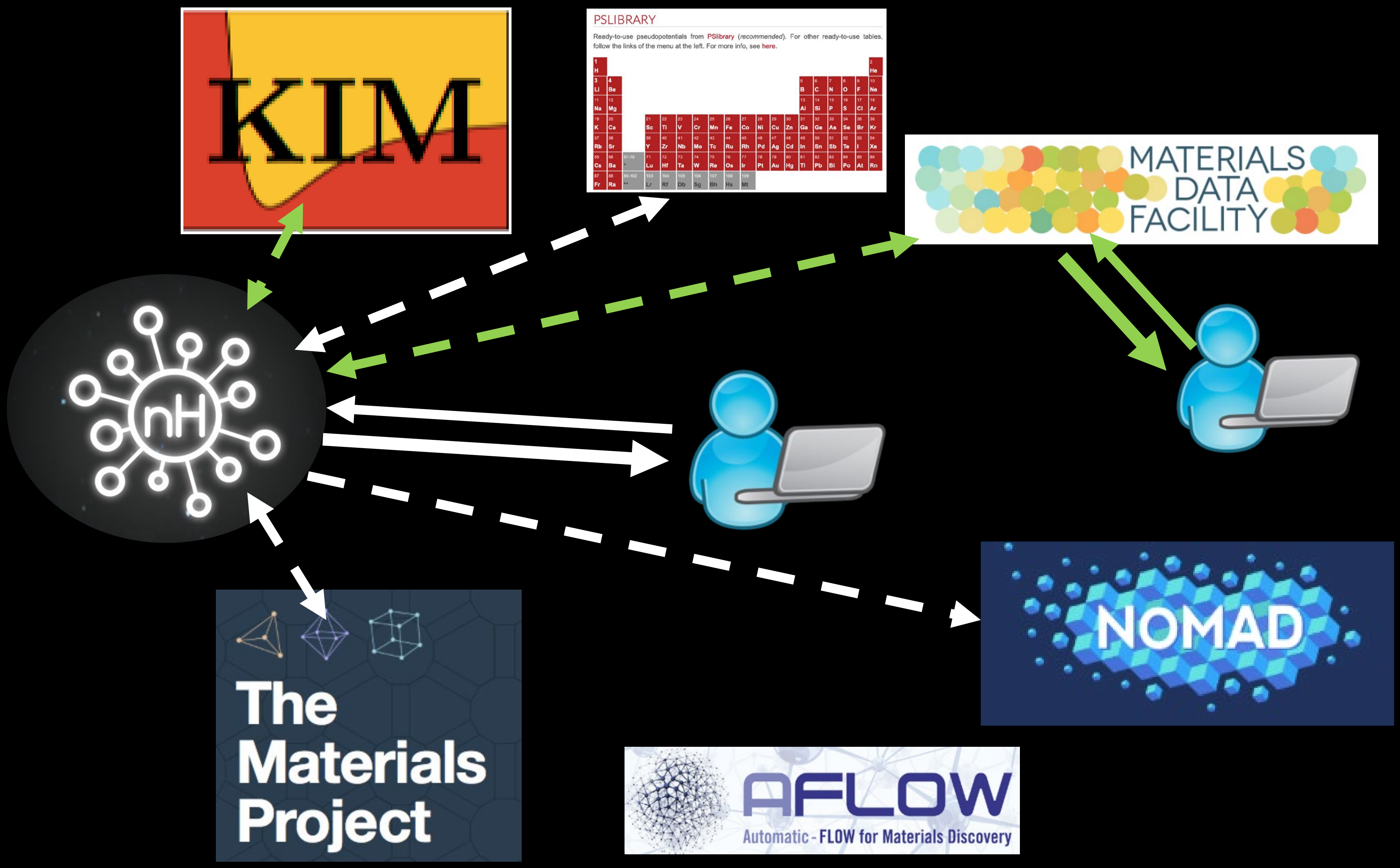
16 NNCI Sites
13 Partners
16 States
69 Facilities
>2,200 Tools

National Nanotechnology Coordinated Infrastructure

NSF and DOE Quantum Research Centers
2020

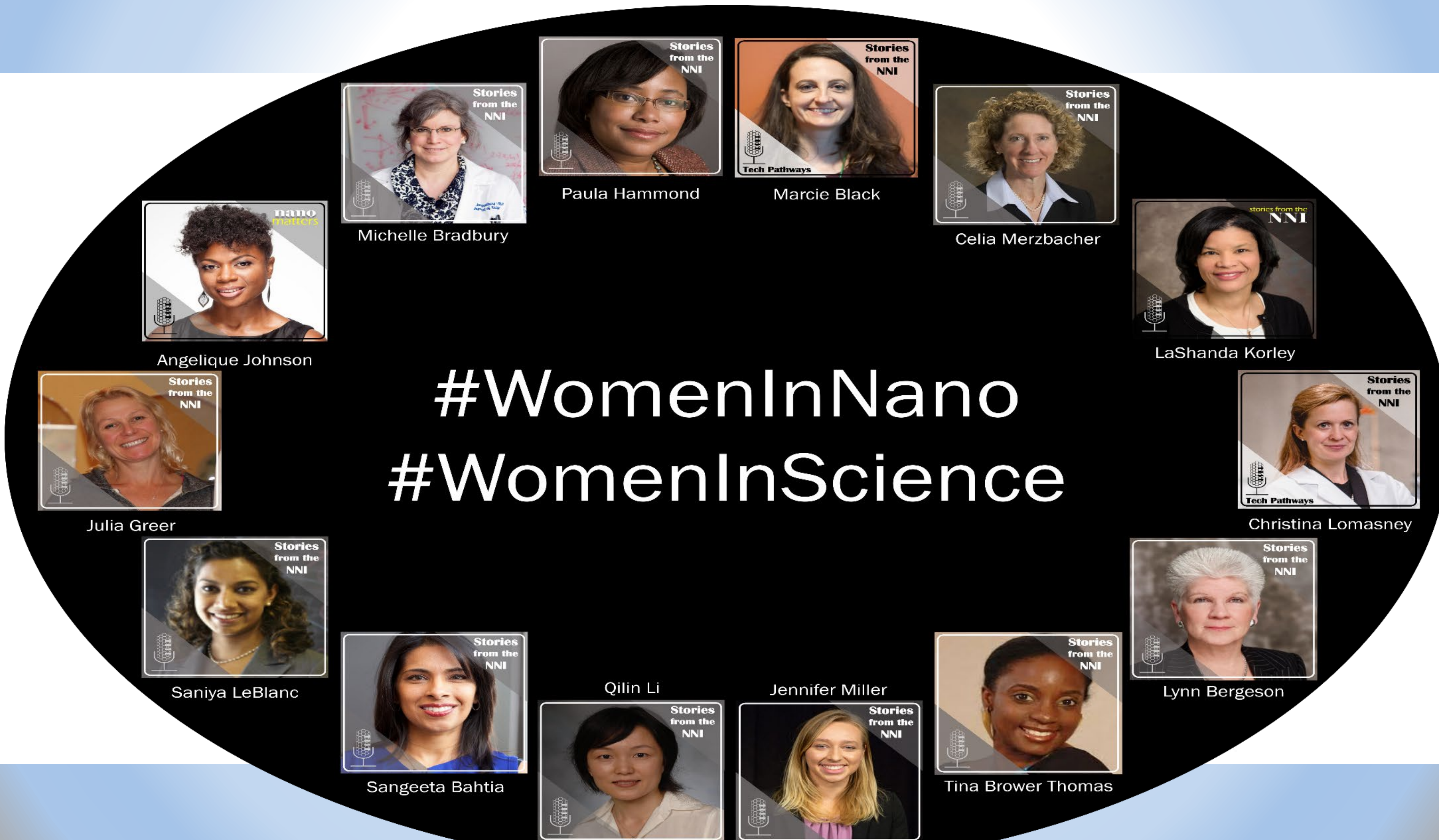
https://science.osti.gov/Initiatives/QIS/QIS-Centers

A cyber ecosystem for nano science & engineering



Women in Nanotechnology

https://www.nano.gov/womens-history-month



nano.gov/podcasts

Several non-technical challenges

Funding challenge: as the use of nanotechnology has diffused in economy, there focus on upstream concepts, common fundamental research, and new methods needs to be maintained

Collaboration and competition challenge: as applied research and development increase, the tension between collaboration and competition increases

Translational speed challenge: as the benefits of R&D are invers proportion with the time of implementation, building a flexible, general-purpose infrastructure for fast design, nanomanufacturing and people training is essential

Translational opportunities at NSF:
Knowledge leads to action

I-CORPS

Americas Seed Fund SBIR.STTR

Convergence Accelerator

CyberCorps

Civic Innovation Challenge

nano3

2020-2030

NBICA systems with emerging behavior

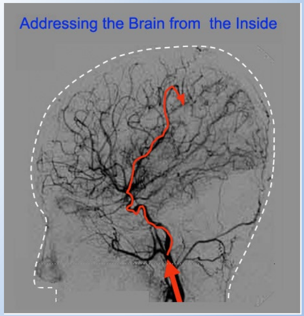
Research opportunities (examples)

- Evolutive nano-bio-AI-robotic systems
- Use *hybrid bio-nanosystems* (viruses, bacteria, ..), synthetic biology & neurotechnology
- Control of DNA , RNA, tissues at the nanoscale
- Human enhancement, including physic-medical, brain potential, behavior, individualized medicine, others
- Earlier detection of illnesses, artificial organs & expand life expectancy
- Intelligent working and urban environments

Challenge: Novel technologies from the nanoscale require new responsibilities

nano3 2020-2030

- **New implications of emerging technologies/ outcomes**
- **Need for integration of R&D and translation**
- **Expand education pipeline:** cross-fields, anticipatory, inclusive
- **Nano-EHS revisited**: for larger nano- structures, composites, devices; affected by digital technologies, AI and robotics, effects on bio- and eco- ethics



- **Nano-ELSI is increasingly important**: ethical, economic, legal, safety, human development
- **Nano-convergence**: essential changes in evaluating and governing the risk, new organizations, and a global view

nano3
2020-2030

Several S&T trends

- Explore foundational principles not yet understood
- Hierarchical manufacturing using modular NBICA
- Sustainability nanotechnology: recycle, water, energy, materials, clean environment, nano metals & plastics..)
- Gene editing in medicine, agriculture, energy
- Brain–to-brain and brain-machine communication
- Quantum entanglement, communication and computing
- NT for smart systems: general purpose AI and Int-Aug
- Convergence with other foundational technologies

Related publications

1. ***"Nanotechnology: Convergence with Modern Biology and Medicine",*** (Roco, Current Opinion in Biotechnology, 2003)
2. ***NANO1: "Nanotechnology research directions: Vision for the next decade"*** (Roco, Williams & Alivisatos, WH, 1999, also Springer, 316p, 2000)
3. ***NANO 2020**: "**Nanotechnology research directions for societal needs in 2020**"* (Roco, Mirkin & Hersam, Springer, 690p, 2011a)
4. ***NBIC**: "**Converging technologies for improving human performance: nano-bio-info-cognition**"* (Roco & Bainbridge, Springer, 468p, 2003)
5. ***CKTS**: "**Convergence of knowledge, technology and society: Beyond NBIC**"* (Roco, Bainbridge, Tonn & Whitesides; Springer, 604p, 2013b)
6. ***"The new world of discovery, invention, and innovation: convergence of knowledge, technology and society"*** (Roco & Bainbridge, JNR 2013a, 15)
7. ***"International perspective on nanotechnology papers, patents, and NSF awards (2000–2016)"*** (Zhu, Jiang, Chen & Roco, JNR 2017, 19-370)
8. ***Proc. NSF NSE Grantees** Dec. 2019, available on www.nseresearch.org/2019/*
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